ERICSSON

September 2, 2016

Ex Parte

Marlene H. Dortch, Secretary
Federal Communications Commission
445 12th Street SW
Washington, DC 20554

Re: Office of Engineering and Technology and Wireless Telecommunications Bureau Seek Information on Current Trends in LTE-U and LAA Technology ET Docket No. 15-105

Dear Ms. Dortch:

In August, Ericsson concluded an extensive series of LTE-U /Wi-Fi coexistence tests. We are filing the results from those tests in the hope that the Commission will find the data valuable as it proceeds with its consideration of LTE technology in unlicensed bands.

In summary, the results of our testing of channel selection, reselection and co-channel operation demonstrate that LTE-U will fairly coexist with Wi-Fi. The channel selection and reselection tests demonstrate that LTE-U channel selection is an extremely effective coexistence procedure, even in extremely dense deployments. The co-channel testing demonstrates that LTE-U has no more impact on a Wi-Fi end user's experience than another Wi-Fi Network.

The tests were performed in a variety of different radio conditions, both in labs and in live networks. They were designed to align as closely as possible with the Wi-Fi Alliance LTE-U coexistence test plan.

We hope these test results will help abate the concerns that have slowed the process of bringing this technology to market, where it will enhance millions of users' experiences and improve the efficiency of 5GHz spectrum use.

Respectfully submitted,

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Ericsson LTE-U Wi-Fi Coexistence Testing Results

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1 Introduction

LTE-Unlicensed (LTE-U) utilizes LTE-Advanced Carrier Aggregation technology to aggregate LTE carriers on a licensed band with LTE carriers over the 5 GHz unlicensed band. With this, end users will receive the excellent performance that they are used to receiving over LTE and data speed bursts made available through the use of unlicensed spectrum.

Given the amount of 5 GHz spectrum available, using approximately 4 percent of the 5 GHz band, LTE-U can provide up to a 135 Mbps speed increase – a speed increase to be added (or aggregated) with the data speed of the underlying LTE licensed band.

LTE-U is anticipated to be of high interest to end users and network operators, and LTE-U is capable of playing an important role in supporting the growth of indoor data traffic.

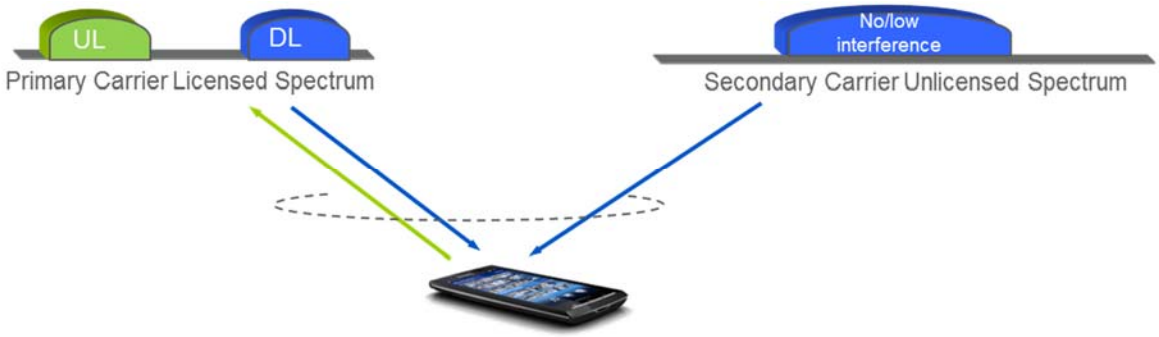

Figure 1 LTE-U Primary and Secondary Cell Operation

As seen in the diagram above, LTE serves as the primary carrier on the licensed spectrum which ensures robust mobility and performance. The LTE primary carrier can either be served by a macro cell, or a small cell. The primary cell serves both Uplink (UL) and Downlink (DL) traffic.
This LTE primary carrier supports:

- Reliable control signaling
- Mobility
- Robust / real-time user data with LTE QoS (Quality of Service)

LTE on the unlicensed band serves as a secondary carrier and provides bursts in the data speed to increase the delivery speed of the data payload. The LTE-U secondary cell serves DL traffic only.
In addition, LTE also monitors the quality of the unlicensed channels and can deliver QoS sensitive applications over the unlicensed band if the quality of the unlicensed channel is sufficient.

LTE-U has been designed to achieve fair sharing between LTE and Wi-Fi and other technologies within the 5 GHz band, to benefit all users. The goal is to impact Wi-Fi end users experience no more than an additional Wi-Fi network would do on the same channel.

To accomplish this, LTE-U has defined a technology neutral 2 step approach to ensure Fair Sharing:
First, LTE-U base stations analyse the available 5 GHz carriers, and intelligently select the least utilized carrier(s) for operation.

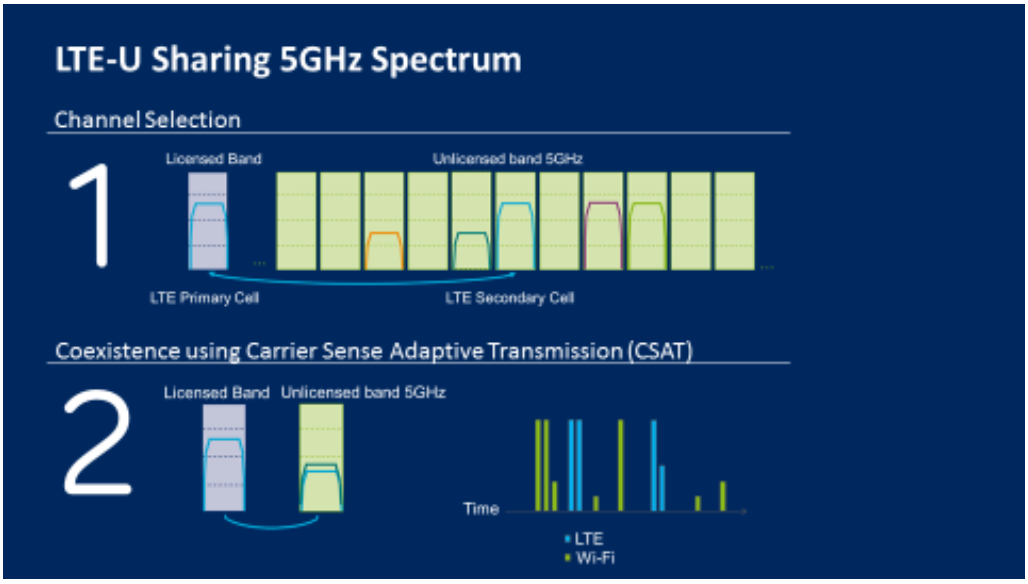

Figure 2 LTE-U Two Step Coexistence procedures

Second, once the LTE-U base station has selected and started operation on the unlicensed carrier, the Carrier Sense / Adaptive Transmission (CSAT) transmit duty cycle is continuously adjusted based on the transmissions of other devices on the channel.

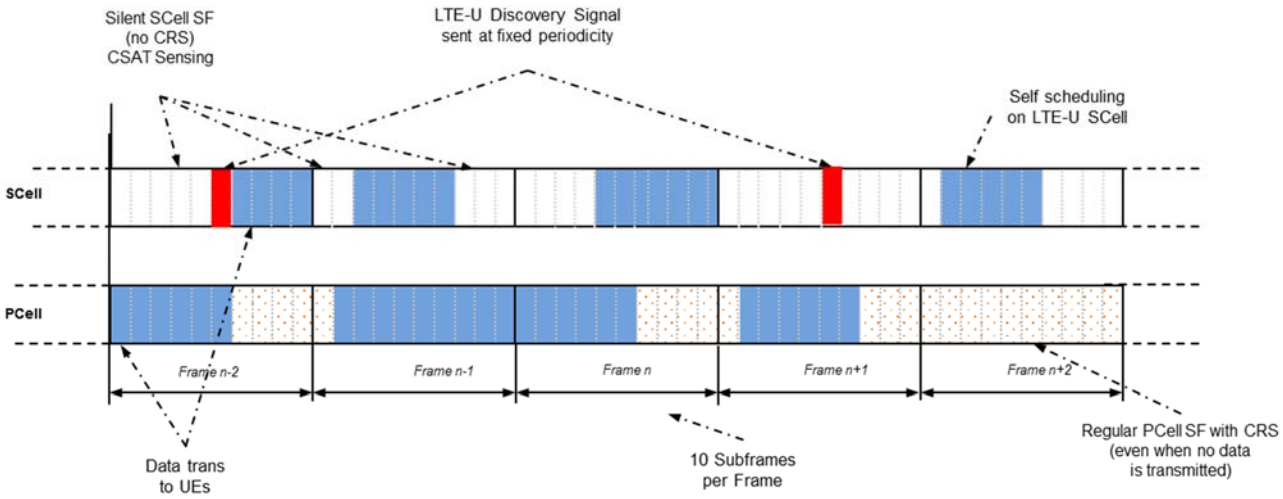

Figure 3 LTE-U Primary & Secondary Cell Transmissions

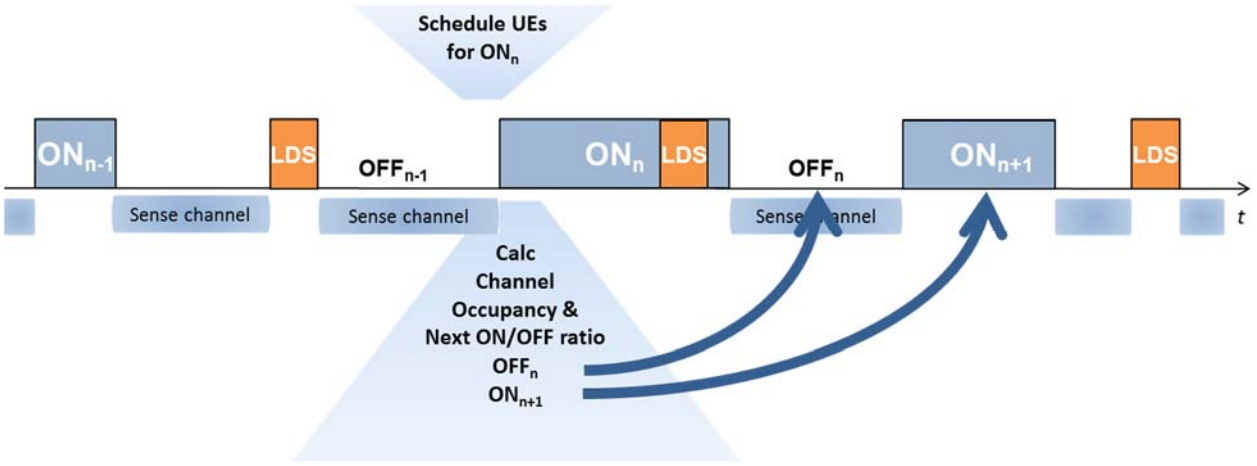

Figure 4 LTE-U CSAT Operation

As required by the LTE-U Forum specifications, LTE-U devices have a maximum transmit duration of 20ms and a minimum sense duration of 2ms. In this testing, the LTE-U base station has a maximum transmit duration of 18ms. The transmit duration is continually adapted in steps of 1ms.

This paper presents the results from three different lab and live network LTE-U test activities showing LTE-U channel selection, reselection and the adaptation of the CSAT duty cycle during operation under different channel conditions and traffic patterns.

The tests followed the intent of the WFA LTE-U Coexistence Test Plan with modifications to make the tests practical and executable in the different test environments.

Tests were performed in varying radio conditions above and below -72dBm.

2 Content

1.1. Conducted Lab Testing

Figure 5 Customer test facility US

Extensive testing was performed in a controlled lab environment in order to characterize the equipment in a repeatable test environment. The RF links were conducted using double shielded coaxial cables. Wi-Fi and LTE-U equipment were isolated from external interference in anechoic chambers. Programmable variable attenuators were used to accurately control the signal levels at each receiver.

The LTE Primary Cell was in band 2, 5MHz (providing approximately 35 Mbps of capacity).

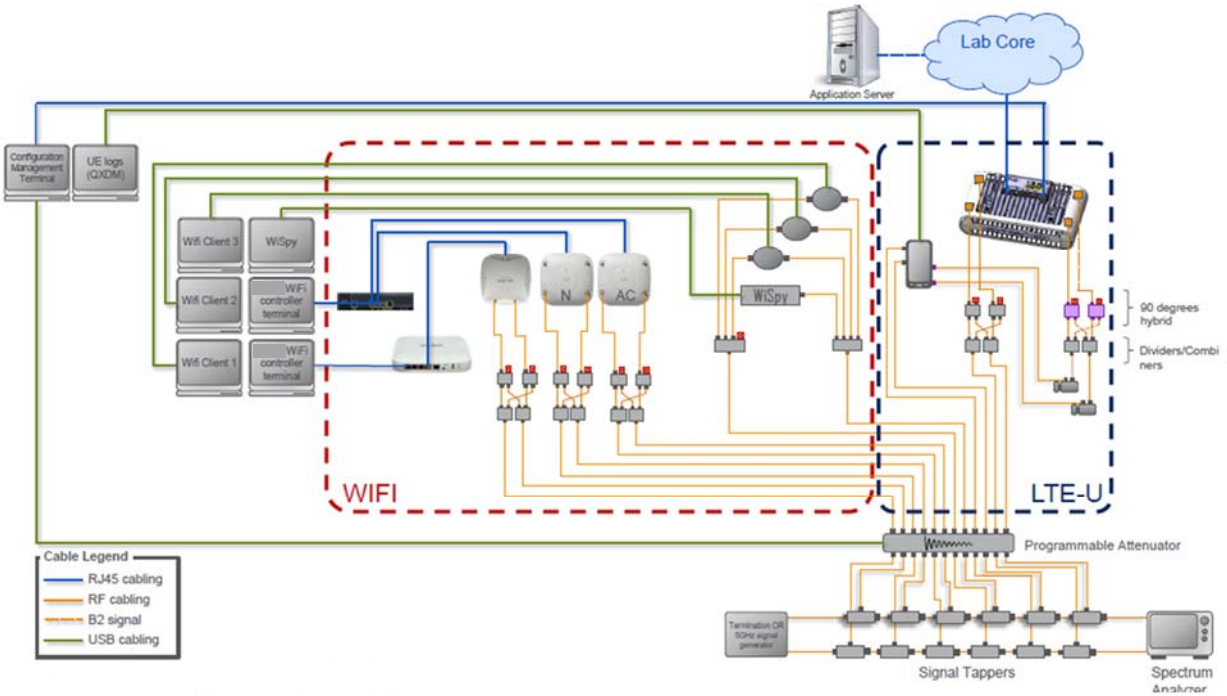

Figure 6 Lab RF and IP Connectivity

First several Wi-Fi – Wi-Fi coexistence tests were conducted in order to establish the coexistence baseline to which LTE-U will be compared. Several different scenarios were tested including multi-vendor Wi-Fi nodes, UL, DL and different 802.11 specification generations, e.g. 802.11ac, 802.11n.

Unless otherwise stated, full buffer UDP traffic was used on each link used in the test and the traffic was generated by an iXChariot traffic generator.

1.1.1. Multi-Vendor 802.11n DL UDP Baseline.

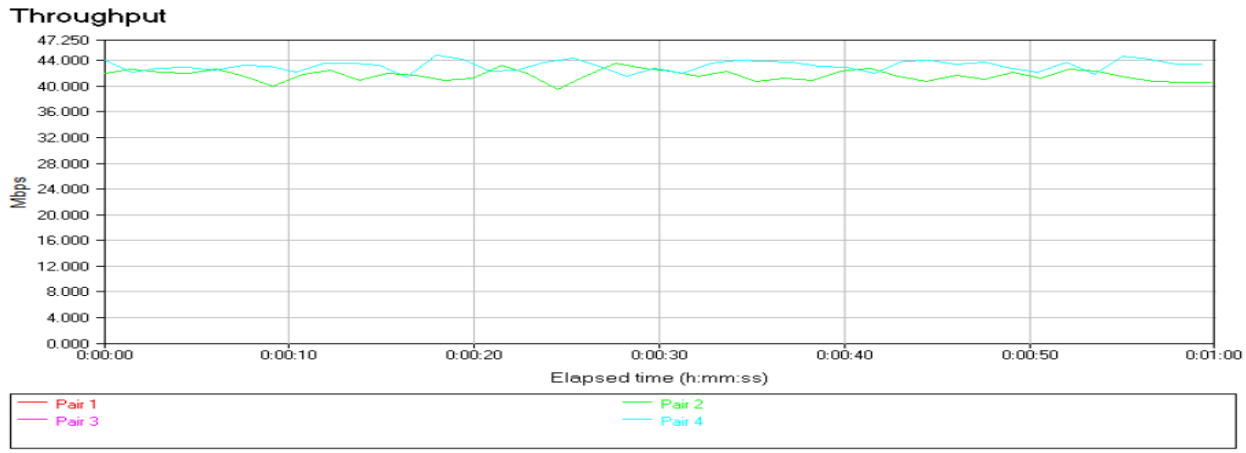

Figure 7 Wi-Fi 802.11n Baseline Throughput

The results show that the different vendors coexist well with average throughput of 41.7Mbps for vendor “A” (green) and 43.2 Mbps for vendor “C” (blue). The difference between the two networks average throughput is < 5%. The total average throughput of both networks is 84.9 Mbps

1.1.2. Multi-Vendor 802.11n and 802.11ac Wi-Fi UL Baseline

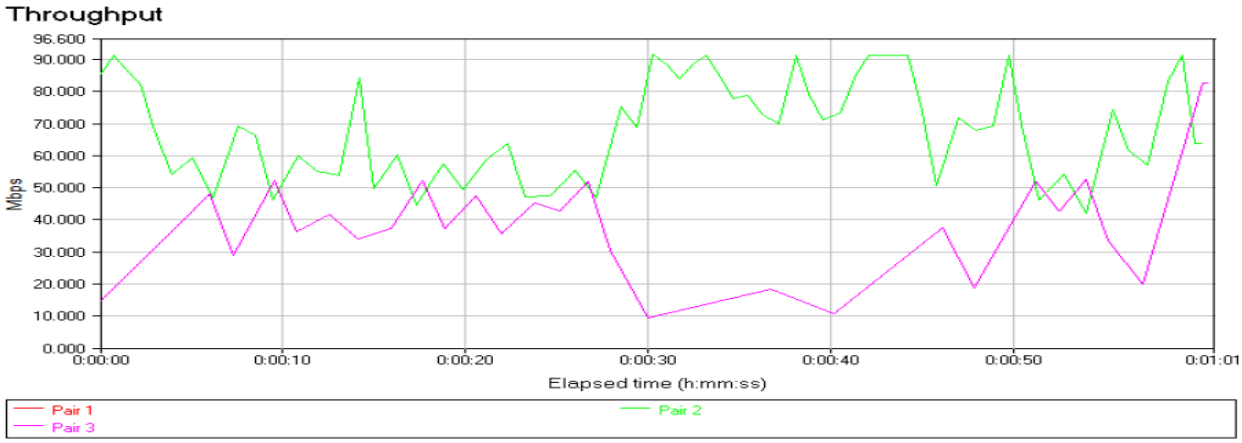

Figure 8 Wi-Fi 802.11n and 802.11ac Baseline Throughput

Vendor “A” (green) achieved 66.2 Mbps on average while vendor “C” (purple) 802.11ac achieved 29 Mbps on average, but as can be clearly observed, the devices throughput was highly variable (vendor “A” min 42 Mbps / max 91.7 Mbps, vendor “C” min 9.5 Mbps / max 82.8 Mbps).

1.1.3. Multi-Vendor 802.11n UL and 802.11ac DL Baseline

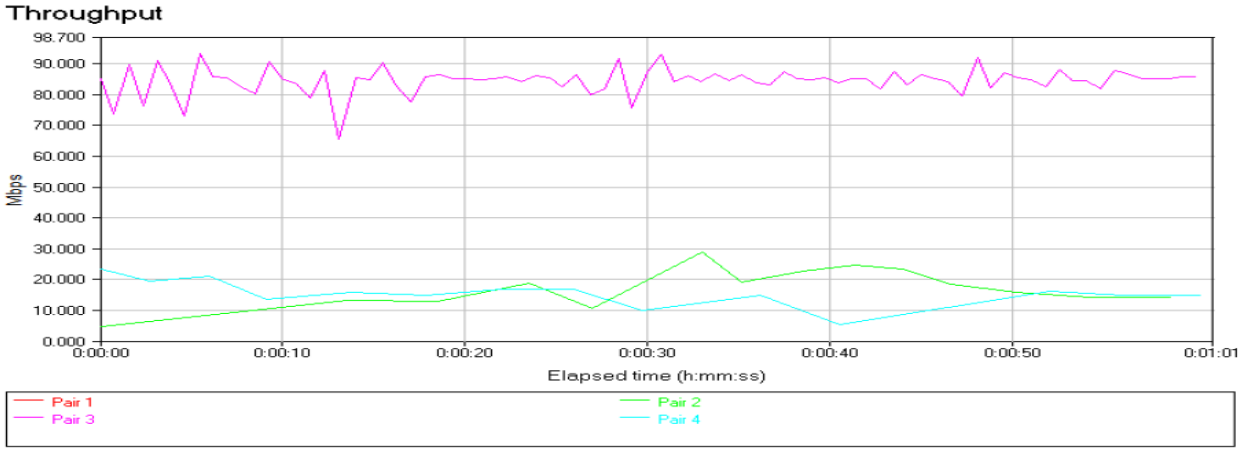

Figure 9 Wi-Fi Mixed 802.11n and 802.11ac UL/DL Baseline Throughput

In this baseline test, an 802.11ac device performing DL traffic was introduced to coexist with two 802.11n nodes performing UL transmissions.

The results show the 802.11ac device (purple, vendor “C”) achieving 82.3 Mbps DL on average while the 802.11n devices (green vendor “A” and blue vendor “C”) achieving 14.2 Mbps and 13.8 Mbps UL on average. The 802.11ac performance is also quite variable (~30%).

1.1.4. LTE-U Coexistence with Vendor “C” 802.11n DL

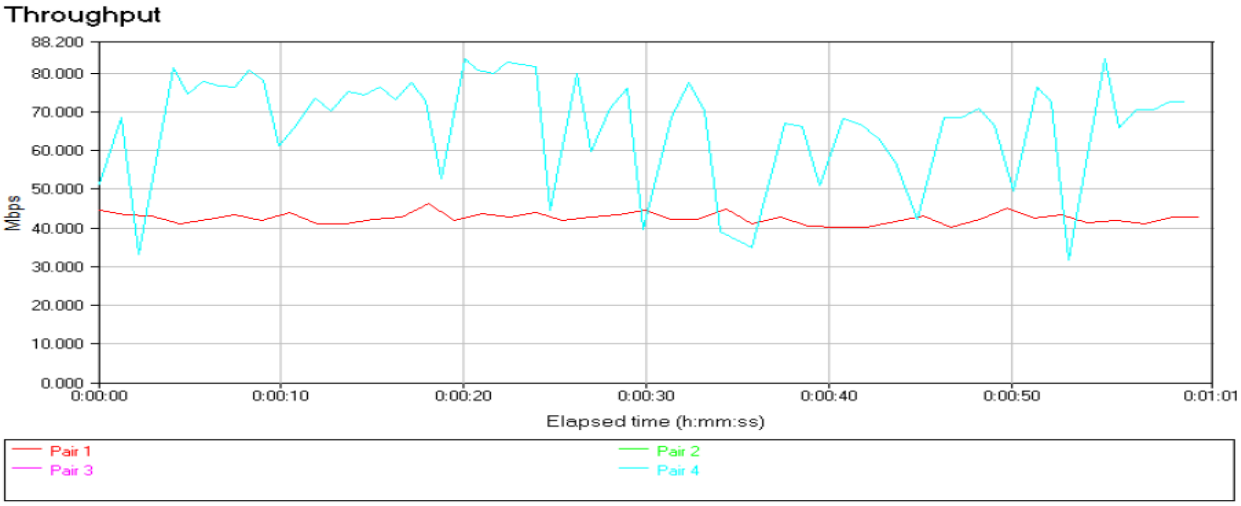

Figure 10 LTE-U and Wi-Fi vendor “C” 802.11n Coexistence Throughput

This test measured the coexistence performance of the LTE-U base station (red) while co-channel with an 802.11n AP (blue vendor “C”) and STA.

The average throughput of the 802.11n DL link is 63.5 Mbps (min 31.7 Mbps / max 83.5 Mbps). Compare this with the results from 1.1.1 where the average throughput of the 802.11n link when co-channel with another 802.11n link is 43.2 Mbps. When co-channel with an LTE-U network, the 802.11n device from vendor “C” average throughput increases by 20.3 Mbps compared to being co-channel with another 802.11n network from vendor “A”.

The average throughput of the LTE-U base station is 42.5 Mbps (min 31.7 Mbps / max 46.3 Mbps).

The combined average DL throughput of both networks is 106 Mbps compared to the combined throughput achieved in the baseline test in 1.1.1 is 84.9 Mbps – an increase of 21.1 Mbps.

It is thought that the variability in the throughput for the 802.11n link is due to the rate adaptation algorithm implemented by vendor “C”.

1.1.5. LTE-U Coexistence with Vendor “A” 802.11n DL

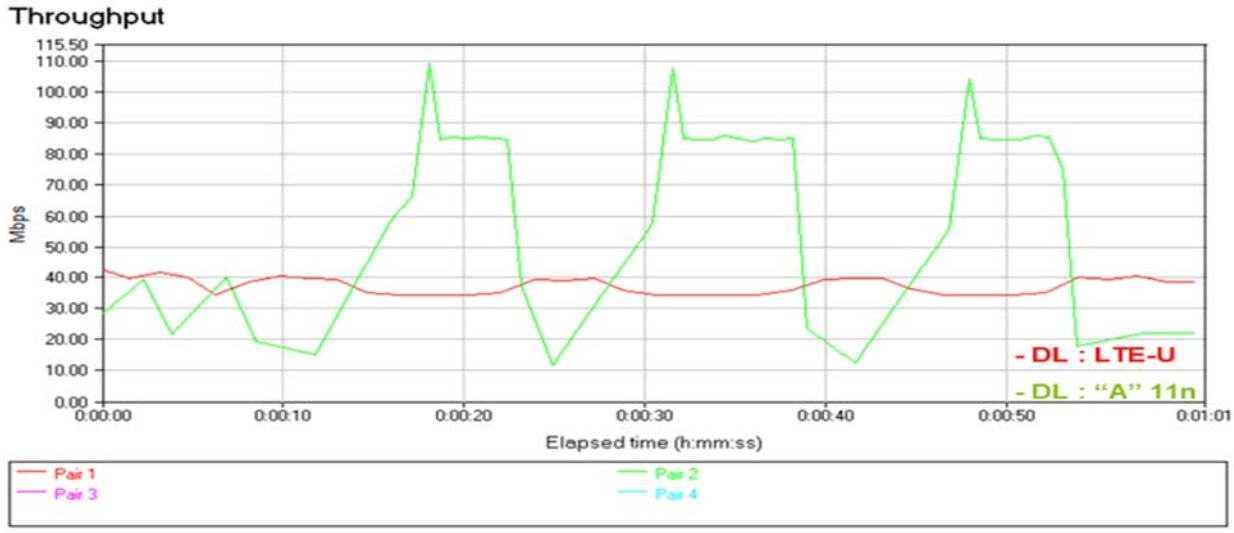

Figure 11 LTE-U and Wi-Fi vendor “A” 802.11n Coexistence Throughput

This test measured the coexistence performance of the LTE-U base station (red) while co-channel with an 802.11n AP (green vendor “A”) and STA.

The average throughput of the 802.11n DL link is 43.5 Mbps (min 11.5 Mbps / max 109.2 Mbps). Compare this with the results from 1.1.1 where the average throughput of the 802.11n link when co-channel with another 802.11n link is 41.7 Mbps. When co-channel with an LTE-U network, the 802.11n device from vendor “A” average throughput increases by 1.8 Mbps compared to being co-channel with another 802.11n network from vendor “C”.

The average throughput of the LTE-U base station is 37.1 Mbps (min 34.2 Mbps / max 42.2 Mbps).

The combined average DL throughput of both networks is 80.5 Mbps compared to the combined throughput achieved in the baseline test in 1.1.1 is 84.9 Mbps – a decrease of 4.4 Mbps.

It is thought that the variability in the throughput for the 802.11n link is due to the rate adaptation algorithm implemented by vendor “A”.

1.1.6. Baseline and LTE-U Coexistence Throughput with Three Networks

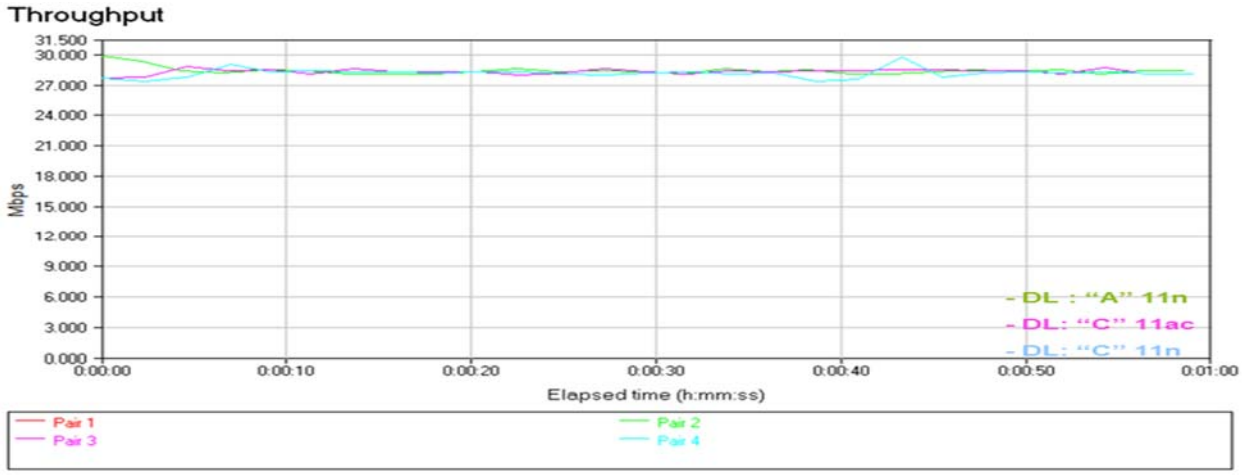

Figure 12 Wi-Fi Multi-Vendor Baseline Coexistence

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)
All Pairs	84.486	27.340	29.867
Pair 1	n/a	n/a	n/a
Pair 2	28.420	28.073	29.867
Pair 3	28.327	27.649	28.871
Pair 4	28.179	27.340	29.754

- DL : Vendor "A" 11n
- DL: Vendor "C" 11ac
- DL: Vendor "C" 11n

Table 1 Baseline Throughput of three Wi-Fi networks coexisting

In the baseline test, the coexistence performance of three multi-vendor 802.11 networks (802.11n and 802.11ac) is recorded.

One of the 802.11ac networks is replaced with a LTE-U network (base station and UE) and the test is then repeated. The results are recorded below in **Figure 13**.

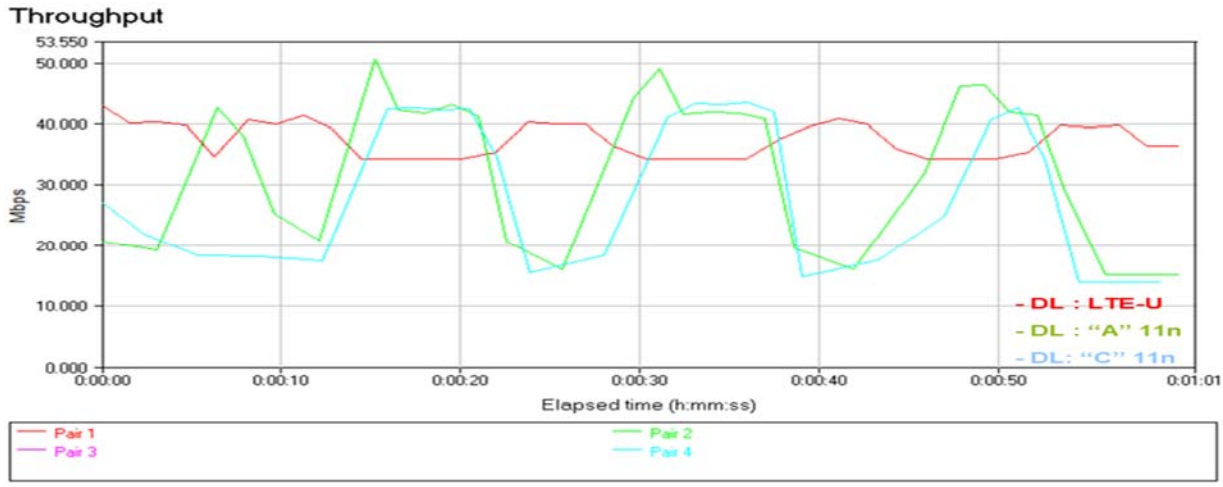

Figure 13 Multi-Vendor Wi-Fi and LTE-U Coexistence Throughput

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
All Pairs	92.622	13.944	50.595	
Pair 1	37.303	34.227	43.044	- DL : LTE-U
Pair 2	29.827	15.206	50.595	- DL : Vendor "A" 11n
Pair 3	n/a	n/a	n/a	
Pair 4	26.021	13.944	43.574	- DL: Vendor "C" 11n

Table 2 Throughput during LTE-U coexistence with two DL Wi-Fi networks

The rate adaption patterns that had been observed in **Figure 10** and **Figure 11** for both vendor "A" and vendor "C" can be clearly seen in the results.

The average throughput of the two Wi-Fi networks when coexisting with LTE-U was within 8% of the baseline results in **Table 1**.

The combined average throughput of the three links is 92.6 Mbps compared to **Table 1** where the combined average throughput is 84.5 Mbps – an increase of 8.1 Mbps.

1.1.7. Coexistence LTE-U with Multi-Vendor 802.11n UDP UL

The purpose of this test was to repeat the three network coexistence test in section 1.1.6 but using UL data instead of DL data.

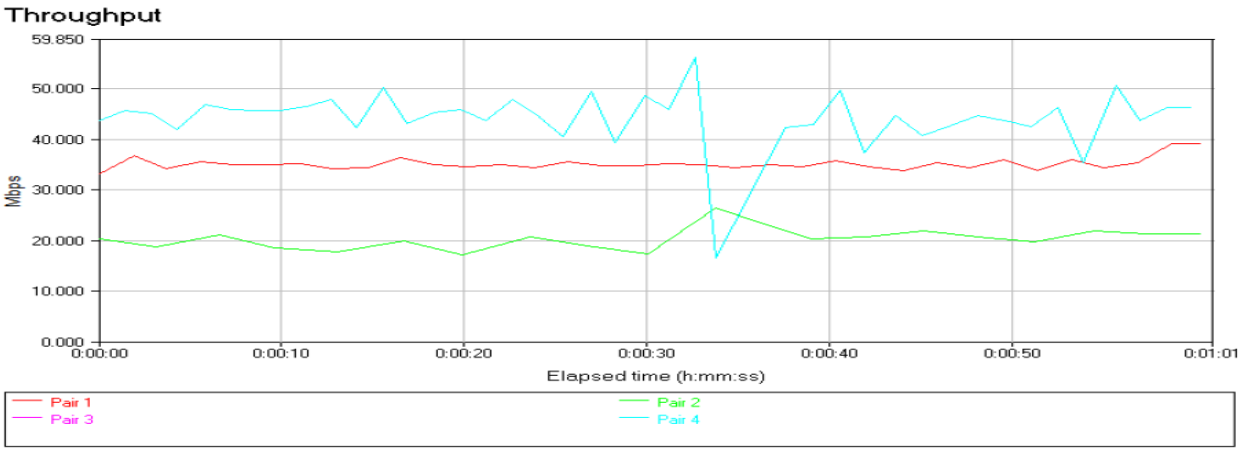

Figure 14 Multi-Vendor Wi-Fi 802.11n and LTE-U Coexistence UL Throughput

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
All Pairs	97.527	16.615	56.140	
Pair 1	35.015	33.252	39.098	- DL : LTE-U
Pair 2	20.144	17.204	26.370	- UL : Vendor "A" 11n
Pair 3	n/a	n/a	n/a	
Pair 4	42.800	16.615	56.140	- UL: Vendor "C" 11n

Table 3 Throughput during LTE-U coexistence with two UL Wi-Fi networks

The first observation is that the 802.11n devices show a much larger variation in average throughput compared with the DL test. In the DL tests the Wi-Fi networks average throughput results were within 10% of each other. In the UL tests, the Wi-Fi networks average throughput results showed a ~22% variance.

Vendor “C” throughput improved from 26 Mbps in **Table 2** to 42.8 Mbps in **Table 3**.

Vendor “A” throughput decreased from 29.8 Mbps in **Table 2** to 20.1 Mbps in **Table 3**.

The LTE-U average throughput was very similar to the DL test results at 35 Mbps (compared to 37.3 Mbps). It is observed that the UL implementation of vendor “C” device used in this test is more robust to interference from LTE-U than the UL implementation of vendor “A”.

1.1.8. Baseline Wi-Fi 802.11n vs. 802.11ac TCP Coexistence

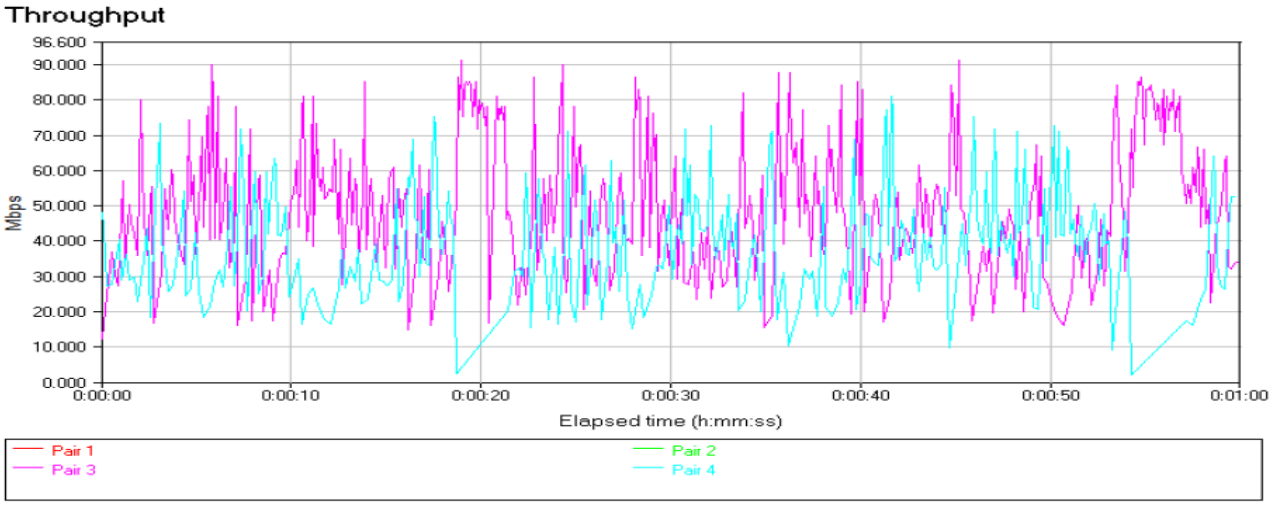

Figure 15 Wi-Fi 802.11n vs. 802.11ac TCP Traffic Coexistence Baseline

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)
All Pairs	75.589	2.214	91.429
Pair 1	n/a	n/a	n/a
Pair 2	n/a	n/a	n/a
Pair 3	44.757	12.167	91.429
Pair 4	31.329	2.214	81.013

UL : Vendor “C” 11ac

UL : Vendor “C” 11n

Table 4 Baseline Wi-Fi Coexistence TCP Throughput

The plots and table of results show a large variability in the throughput of the two Wi-Fi networks. The combined average throughput of both networks is 75.6 Mbps.

1.1.9. Coexistence (TCP) vendor “C” 802.11ac with LTE-U Throughput

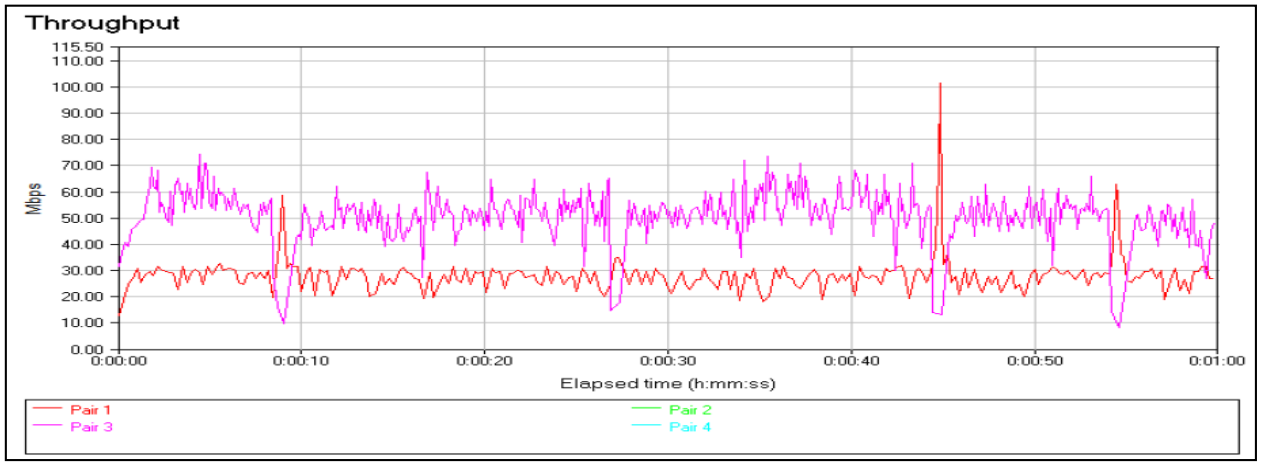

Figure 16 Wi-Fi 802.11ac and LTE-U TCP Traffic Coexistence Throughput

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
Pair 1	27.492	12.982	101.587	- DL : LTE-U
Pair 2	n/a	n/a	n/a	
Pair 3	48.881	8.312	74.419	- UL : Vendor “C” 11ac

Table 5 TCP Throughput with LTE-U Coexistence with Wi-Fi

The average throughput of the Wi-Fi network was 48.9 Mbps – an increase of 17.5 Mbps or 35% compared to the baseline result in 1.1.8.

The combined average throughput of both networks is 76.4 Mbps – almost identical to the baseline result in 1.1.8.

The Wi-Fi network experienced improved performance when coexisting with LTE-U compared to coexisting with another Wi-Fi network.

1.1.10. Summary of Conducted Lab Coexistence Testing

Extensive testing with multiple Wi-Fi nodes from multiple vendors.

Large variances between sharing performance of different Wi-Fi technologies and vendors.

Wi-Fi throughput with LTE-U is very vendor specific – dependent on the devices capabilities.

Lab test results demonstrate LTE-U fair sharing.

	WI-FI + WI-FI	WI-FI + LTE-U
UL TOTAL	94.8 Mbps	97.5 Mbps
DL TOTAL	84.4 Mbps	105.1 Mbps

1.2. Live Air Network Testing, Johannesberg

Figure 17 Live Air Testing Johannesburg, South Africa

The aim of the Johannesburg live network LTE-U test activity was to demonstrate the main aspects of LTE-U technology using Ericsson indoor small cell product. The Test cases covered the following aspects:

- Adaptive Channel Usage
- Dynamic ON/OFF (Co-existence with Wi-Fi)
- Channel Selection (Coverage and Timer based)

A 10MHz Primary licensed cell in band 3 (1800 MHz) from the operator's live network was used in conjunction with a Secondary Unlicensed Cell in 5 GHz band.

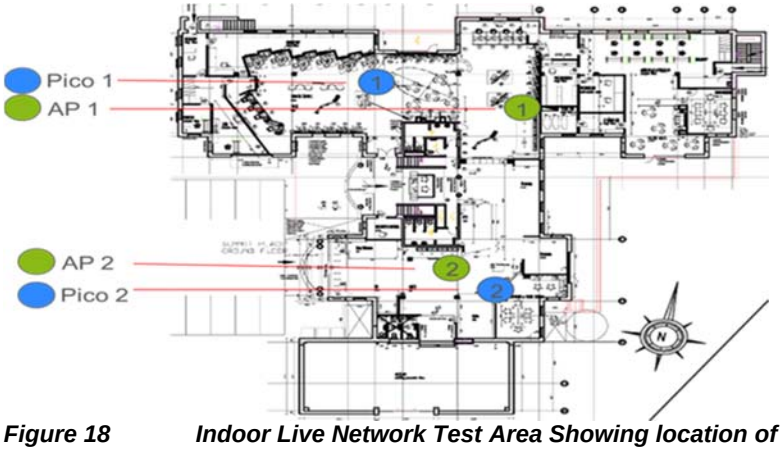

Figure 18 Indoor Live Network Test Area Showing location of Wi-Fi APs and LTE-U base stations

1.2.1. Channel Coexistence Between Wi-Fi and LTE-U

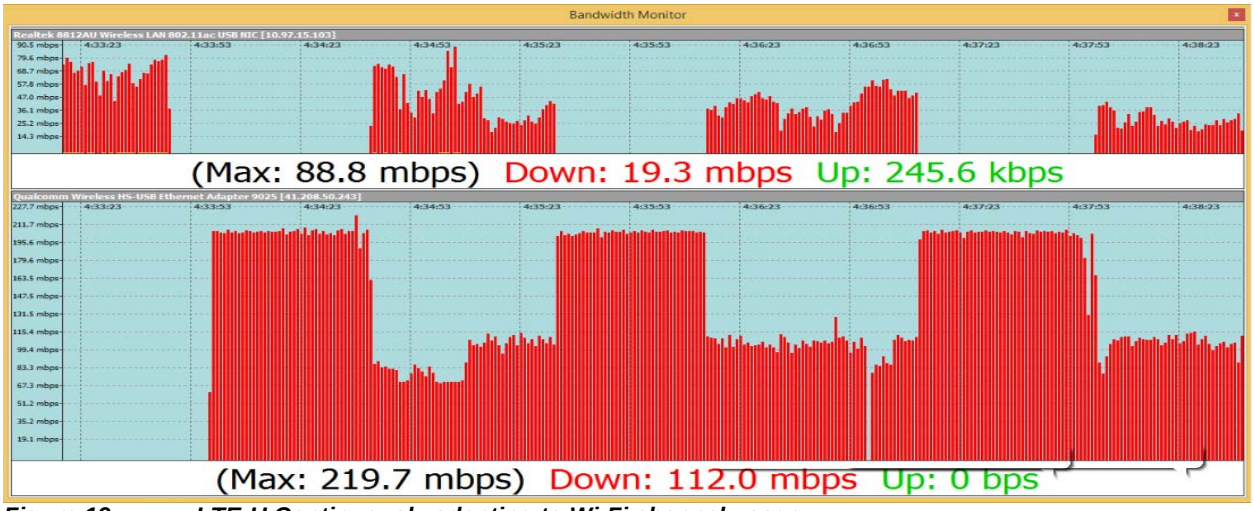

Figure 19 LTE-U Continuously adapting to Wi-Fi channel usage

As shown in the throughput plot above, the average throughput of the Wi-Fi link without LTE-U interference is ~68 Mbps.

The Wi-Fi traffic is halted and LTE-U full buffer traffic started. At approximately 4:34:30, Wi-Fi full buffer traffic is resumed and the LTE-U equipment backs-off in response. The average Wi-Fi throughput during the LTE-U transmission period is ~37 Mbps. The LTE-U throughput drops from 203 Mbps to ~99 Mbps.

Note: these values include the throughput on the licensed primary 10MHz cell – approximately 75 Mbps. At approximately 4:35:30 the Wi-Fi traffic is again halted and we see the LTE-U equipment resume to operate at maximum duty cycle.

This cycle is repeated.

1.2.2. LTE-U channel selection

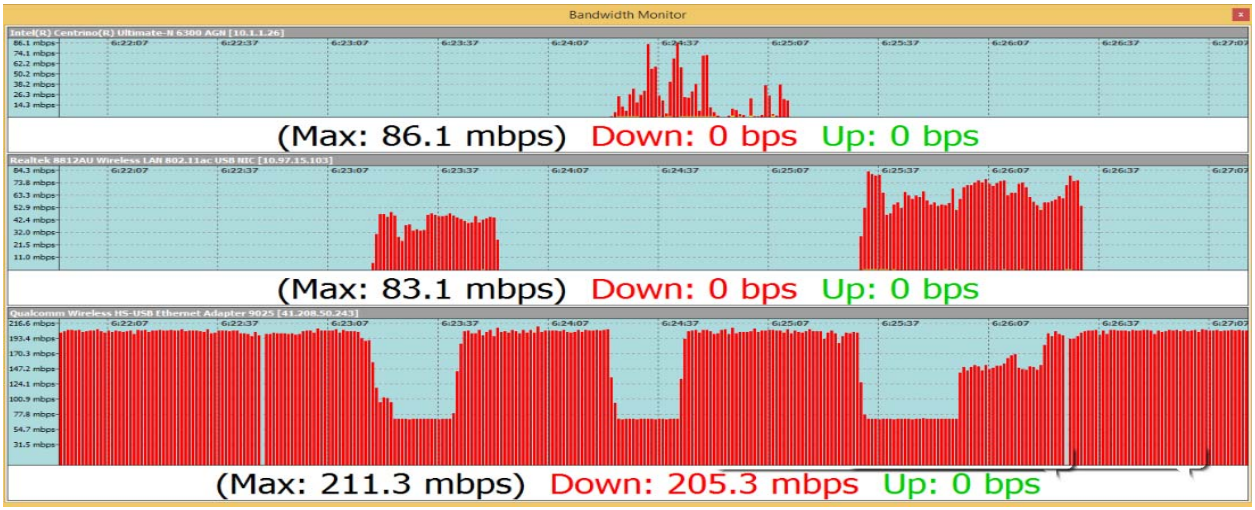

Figure 20 Wi-Fi and LTE-U Throughput during LTE-U Channel Selection and Re-Selection

The following figures trace the timeline of events during the test procedure.

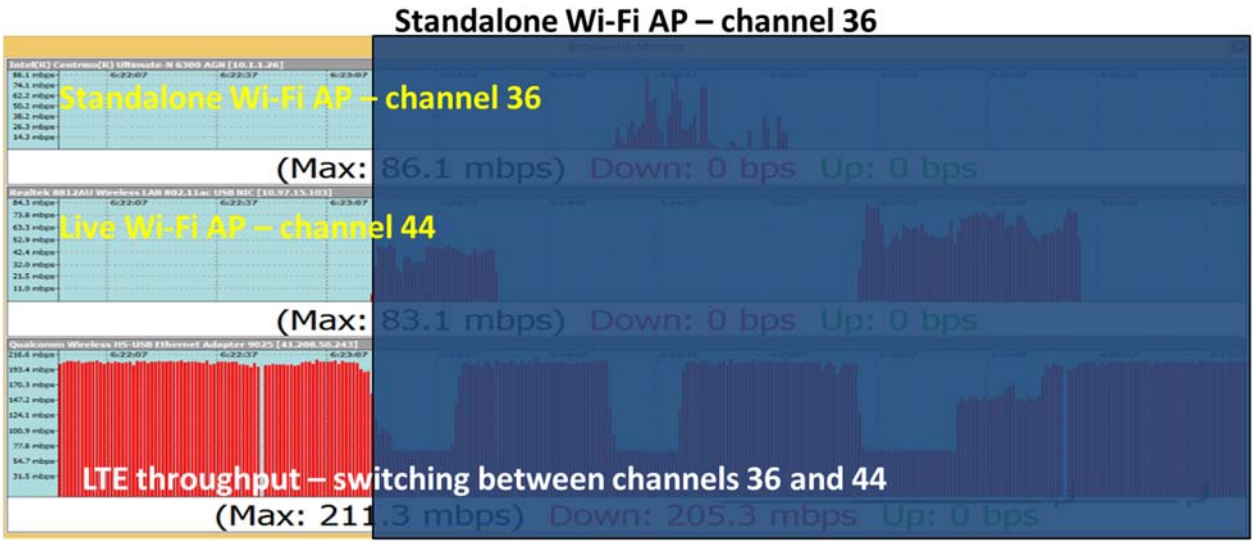

Figure 21 *LTE-U Cell running in channel 44 and using full bandwidth. Both Wi-Fi AP's are not transmitting any data*

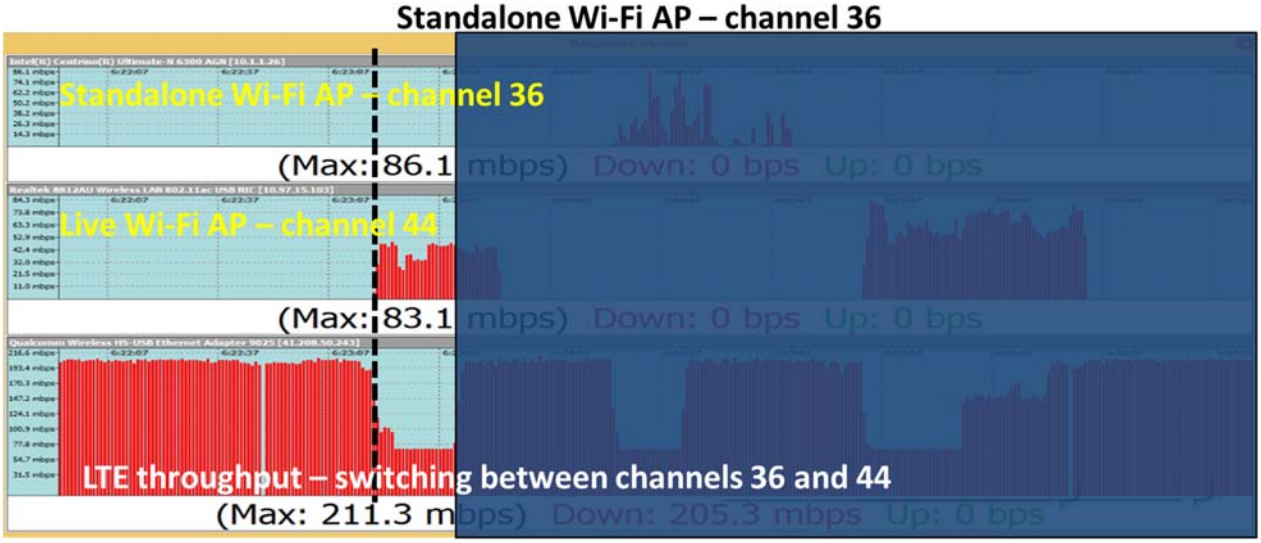

Figure 22 *Live Wi-Fi AP starts transmitting in channel 44. LTE-U Cell backs off immediately and start scanning candidate channels*

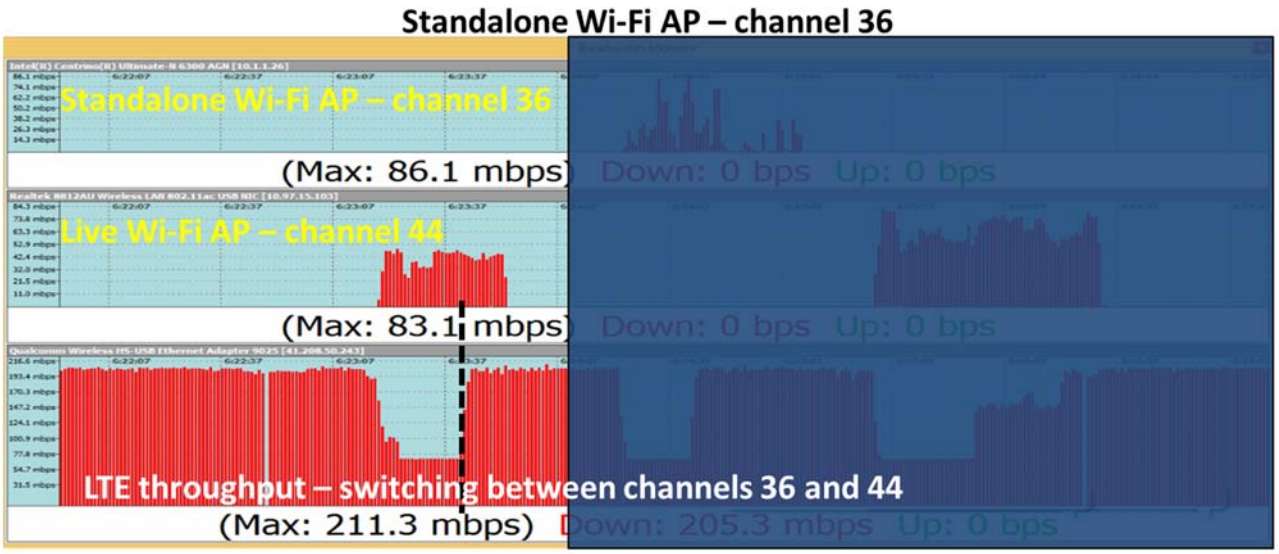

Figure 23 ***Channel re-selection triggered. LTE-U Cell switch to channel 36. Note that Standalone AP is not transmitting in channel 36 yet***

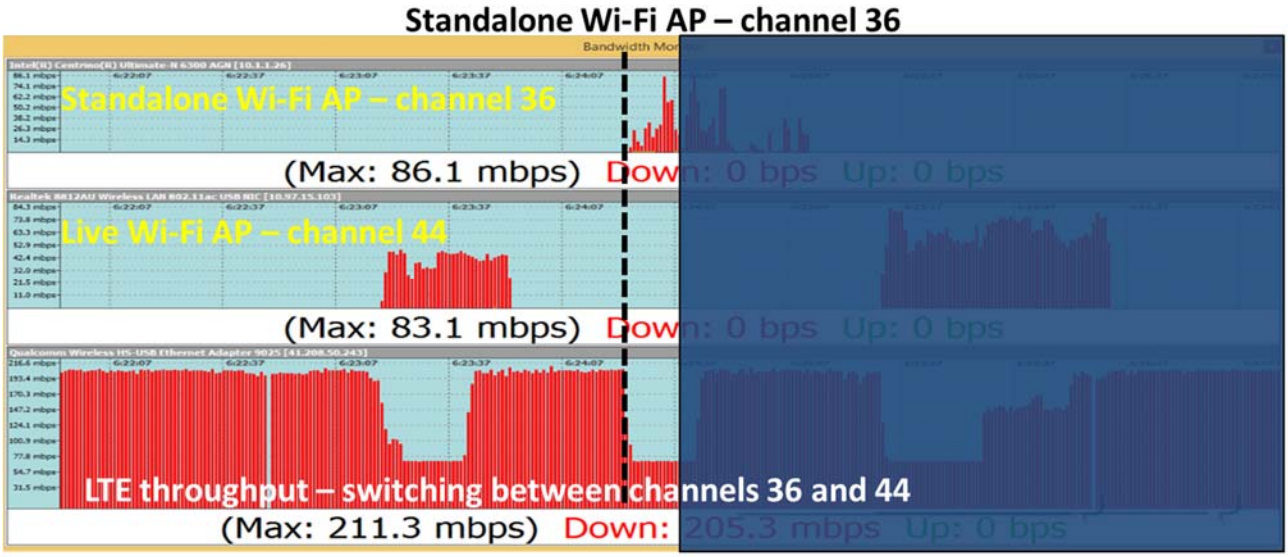

Figure 24 ***Standalone Wi-Fi AP starts transmitting in channel 36. LTE-U Cell backs off immediately and start scanning candidate channels***

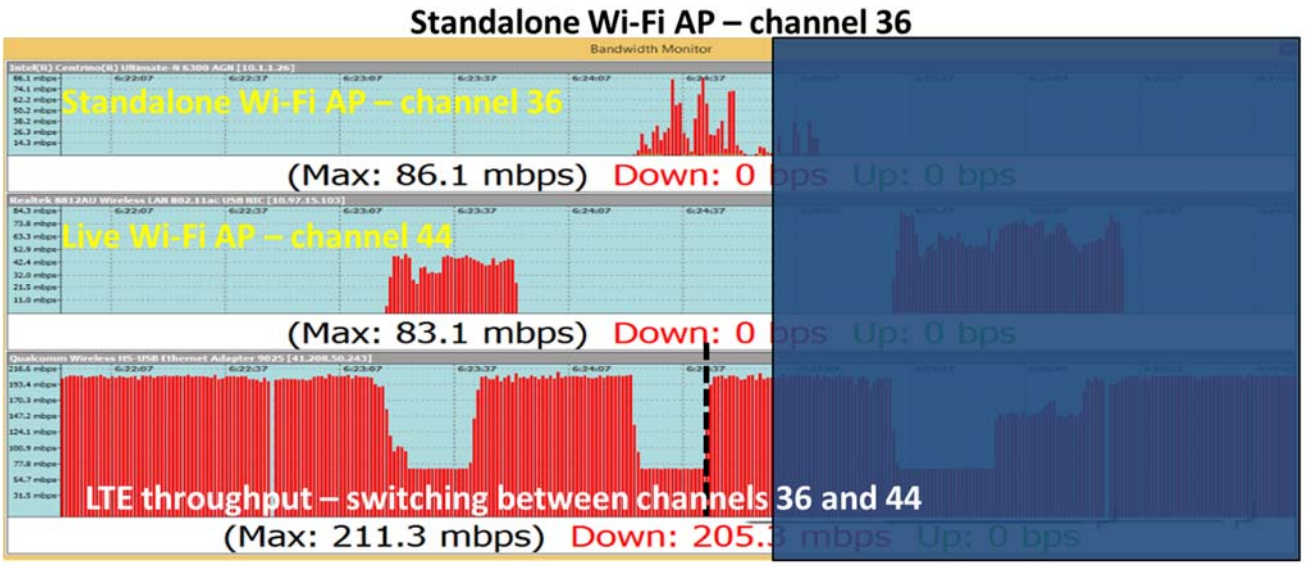

Figure 25 *Channel re-selection triggered. LTE-U Cell switch back to channel 44 since it was clean. Live AP is not transmitting in channel 44 at that time*

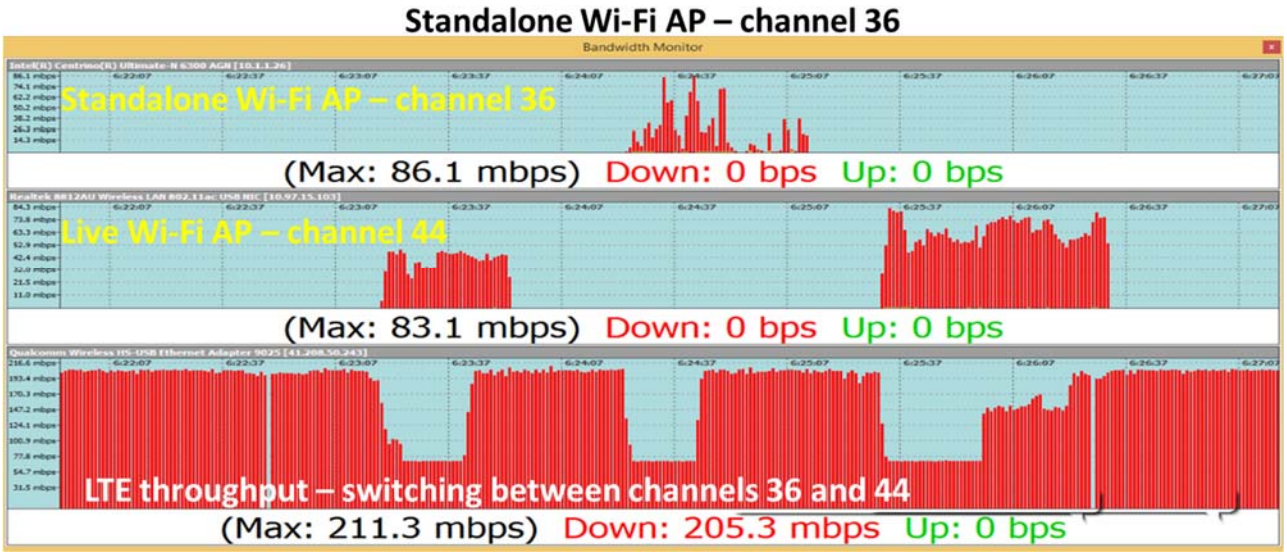

Figure 26 *The procedure continues: LTE-U equipment continues to re-select operating channel based on the received interference*

1.3. Enterprise Live Air Network, USA

Figure 27 *Enterprise Over-the-air Network Testing, USA*

The test area covered approximately 116 standard office cubicles in addition to a number of closed meeting room and storage spaces.

The tests were performed “Over-The-Air” using Live LTE-U and Wi-Fi networks. Two indoor pico LTE-U base stations were ceiling mounted (labelled “prbs4” and “prbs5” in **Figure 28**).

The primary licensed band cell used during the live air trials was 5MHz located in band 2 spectrum. The 5MHz primary cell can achieve data rates of 35 Mbps DL in good RF conditions.

Testing was performed on mobile test stations using defined walk routes encompassing the entire building floor with measurements being recorded during the entire walk route.

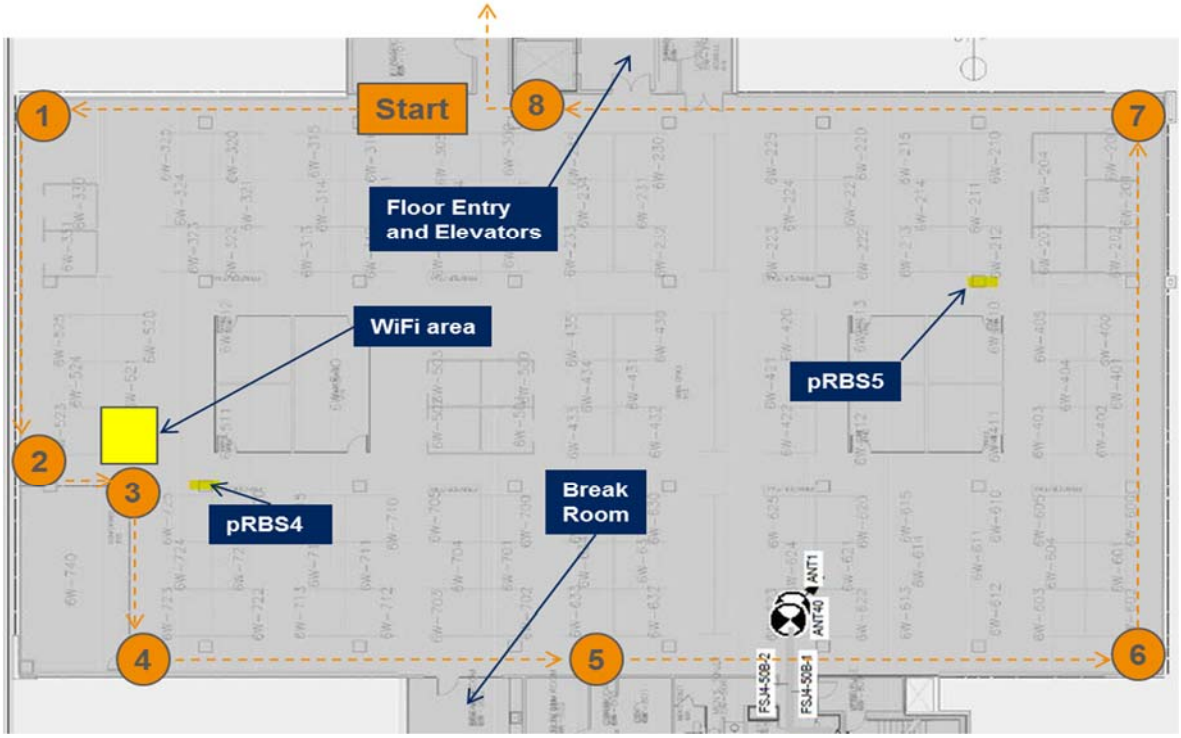

Figure 28 Floor Plan of Enterprise Office Test Area, showing walk route

The following test areas were covered during this test activity:

Num	Test Area	Description	Total Number of:		Field Indoor TC Execution Status		
			Categories	Test Cases (Lab, Indoor and Outdoor)	Planned	Executed	Complete
1	LTE-U_HW	LTE-U Hardware Regression Tests	3	10	9	9	9
2	LTE-U_BASELINE	LTE-U Baseline Tests	2	12	12	11	11
3	LTE-U_COVERAGE	LTE-U Coverage Tests	1	16	7	4	4
4	LTE-U_MOBILITY	LTE-U Mobility Tests	1	15	8	8	8
5	LTE-U_SCHEDULER	LTE-U Scheduler Tests	1	12	12	12	12
6	LTE-U_FEATURES	LTE-U Feature Tests	1	4	4	0	0
7	LTE-U_CH_SELECTION	LTE-U Channel selection Tests	3	25	25	25	25
8	LTE-U_COEXISTENCE	LTE-U Coexistence Tests	6	30	24	24	24
9	LTE-U_SCELL_OFF	LTE-U Opportunistic SDL Tests	2	3	3	3	3
10	LTE-U_COEXISTENCE_HIDDEN_WIFI	LTE-U Coexistence with hidden Wifi	2	6	6	6	6
11	LTE-U_COEXISTENCE_NON_WIFI	LTE-U Coexistence with Non Wifi	2	3	3	0	0
12	LTE-U_STABILITY	LTE-U Stability Tests	2	4	4	4	4
TOTAL			26	140	117	106	106

Table 6 Enterprise Field Trial Test Areas

A total of 106 tests were executed from 117 in total.

A number of tests were not able to be performed due to lack of test equipment or availability of test tools at the time of the trial, e.g. coexistence with not Wi-Fi equipment tests required cordless telephone devices operating in the U-NII-1 or U-NII-3 channel, unfortunately no such devices could be sourced in time for the trials.

The trial test activities started by establishing a set of Wi-Fi baseline throughput tests.

1.3.1. Single node Wi-Fi Baseline coexistence DL full buffer UDP

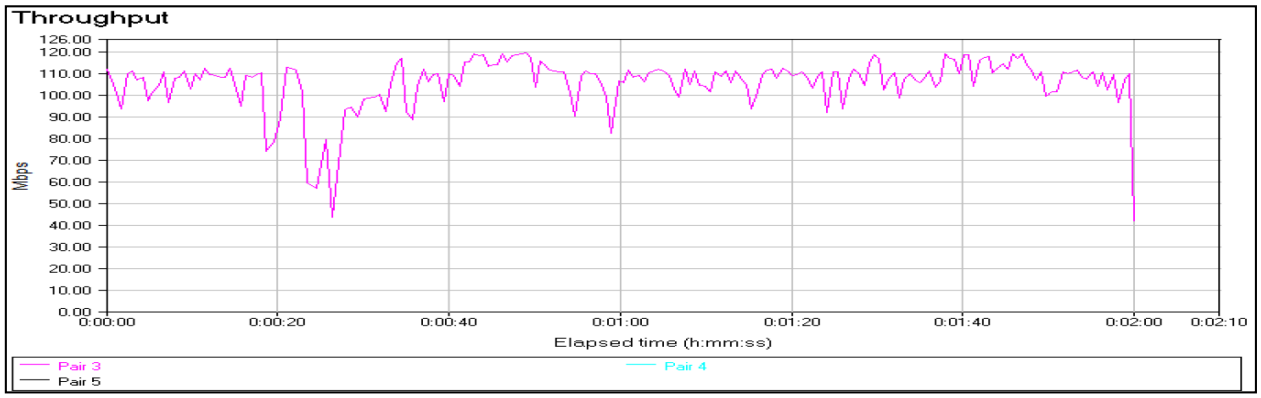

Figure 29 Single Wi-Fi 802.11ac Network Wi-Fi DL Baseline Throughput

In order to establish the throughput of a single Wi-Fi AP and STA utilizing a free channel, a test was performed using a Wi-Fi AP (from vendor “C”) operating in 802.11ac mode with a single Wi-Fi STA.

The results of the single node throughput tests were recorded in **Figure 29**. Vendor “C” 802.11 ac Wi-Fi AP with full buffer DL UDP traffic: Min 42 Mbps / max 119 Mbps, average 105 Mbps.

The plot of the throughput measurements shows a relatively large variance in throughput during the full duration of the test even though there were no other interferers on the channel and the traffic generation tool provided a full buffer flow of identically sized DL UDP packets with near zero jitter.

1.3.2. Multi-Vendor 802.11ac and Wi-Fi 802.11n Baseline coexistence DL UDP

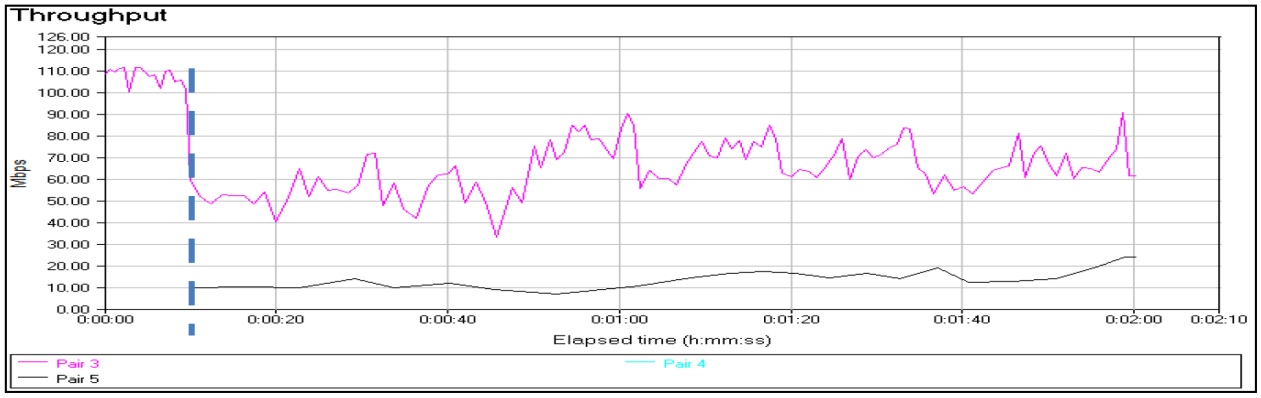

Figure 30 Multi-Vendor 802.11n and 802.11ac Wi-Fi Coexistence Baseline Throughput

Vendor “C” 802.11ac (pink) min 33 Mbps / max during both networks coexisting is 91 Mbps with an average of 58 Mbps (measurements to the left of the blue dashed line ignored).

Vendor “A” 802.11n (black) min 6.7 Mbps / max 24 Mbps, average 12.5 Mbps.

1.3.3. LTE-U coexistence with Wi-Fi 802.11ac

When vendor “A” 802.11n Wi-Fi device is replaced with the LTE-U base station and the same full buffer traffic test was performed the following results were recorded:

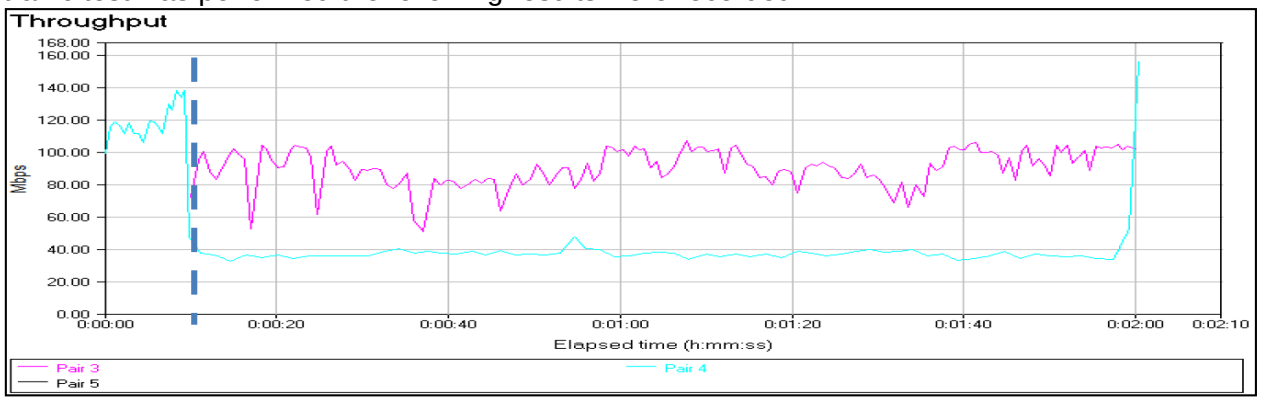

Figure 31 LTE-U and 802.11ac Wi-Fi Coexistence Throughput

Vendor “C” 802.11ac (purple) min 51 Mbps / max 107 Mbps, average 89.5 Mbps.

LTE-U (blue) min 32 Mbps / max during both networks coexisting is 47 Mbps (included licensed primary cell throughput), average 37 Mbps (measurements to the left of the blue dashed line ignored).

The 802.11ac device accounts for 67% of the combined throughput of the two networks.

1.3.4. Baseline Wi-Fi coexistence with three networks

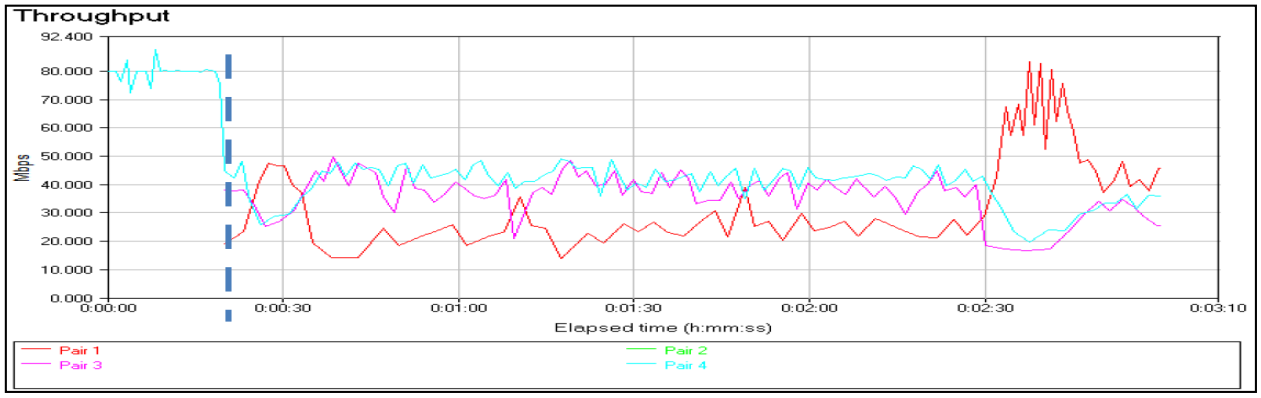

Figure 32 Multi-Vendor 802.11n and 802.11ac Three Network Coexistence Baseline

Vendor “C” 802.11n (red) min 14 Mbps / max 83.2 Mbps, average 29.2 Mbps.

Vendor “C” 802.11ac (purple) min 16.5 Mbps / max 48.8 Mbps, average 35.2 Mbps.

Vendor “A” 802.11ac (blue) min 19.7 Mbps / max during coexistence is 49 Mbps, average 42 Mbps (measurements to the left of the blue dashed line ignored).

The results show quite a variance in time of the three coexisting devices.

1.3.5. LTE-U coexistence with two Wi-Fi networks

When the previous test was repeated with one of the 802.11ac networks replaced with the LTE-U base station, the following results were recorded:

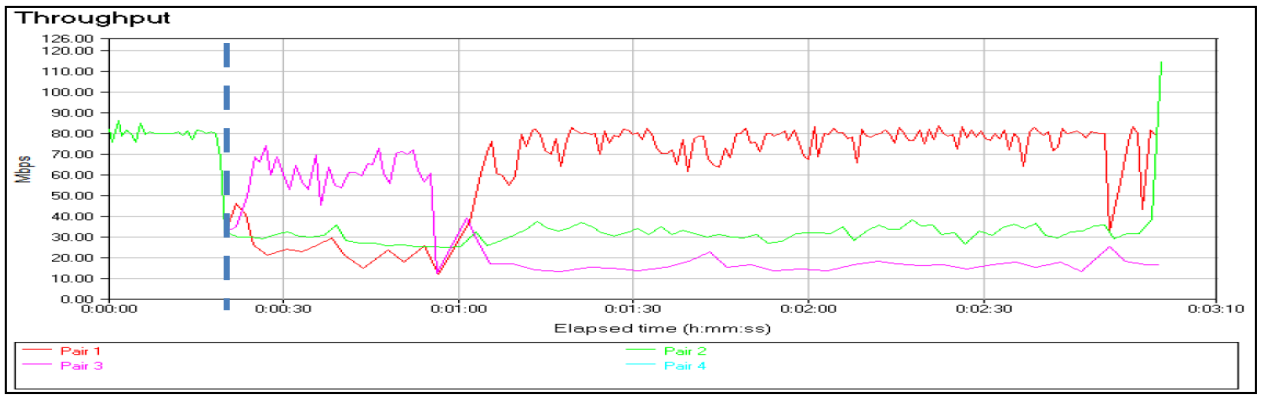

Figure 33 LTE-U Coexistence with Multi-Vendor 802.11n and 802.11ac Wi-Fi Networks

LTE-U base station (green) min 25 Mbps / max during coexistence is 38 Mbps, average 31 Mbps (measurements to the left of the blue dashed line ignored).

Vendor “C” 802.11n (red) min 11.9 Mbps / max 83.5 Mbps, average 60.8 Mbps.

Vendor “C” 802.11ac (purple) min 12.3 Mbps / max 74.1 Mbps, average 25.8 Mbps.

The LTE-U base station accounts for 30% of the combined throughput of the three networks.

1.3.6. LTE-U coexistence with multiple Wi-Fi networks above and below -72dBm

The following baseline test using Wi-Fi nodes all above -72dBm:

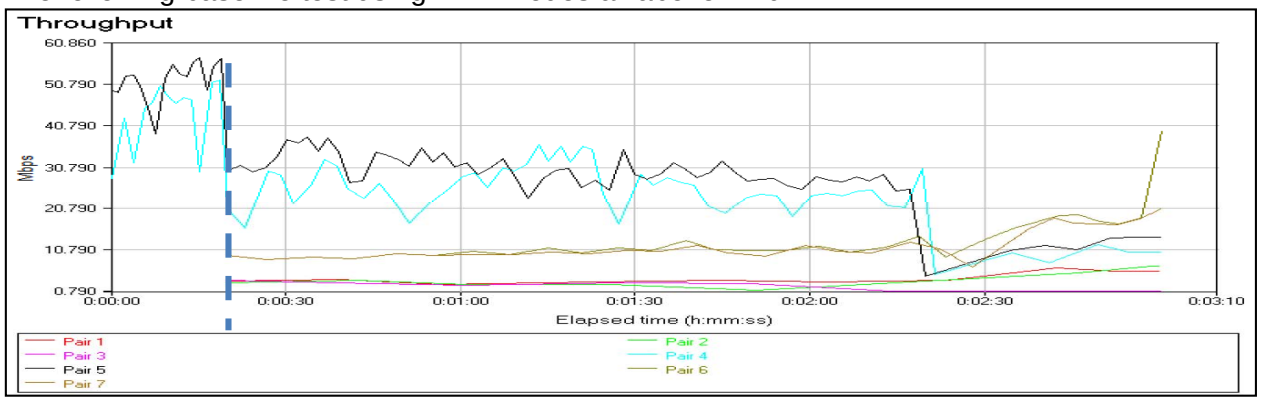

Figure 34 Multi-Vendor 802.11ac and 802.11n Multi-Link Wi-Fi Baseline Throughput

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
All Pairs	78.124	0.802	57.194	
Pair 1	3.472	2.444	6.369	VENDOR "C" 11N
Pair 2	2.471	1.155	6.918	VENDOR "C" 11N
Pair 3	2.229	0.802	3.476	VENDOR "C" 11N
Pair 4	23.391	4.877	51.822	VENDOR "C" 11AC
Pair 5	27.640	4.376	57.194	VENDOR "C" 11AC
Pair 6	11.580	8.425	39.684	VENDOR "A" 11N
Pair 7	10.827	6.614	20.562	VENDOR "A" 11N

Table 7 Multi-Vendor 802.11ac and 802.11n Multi-Link Throughput Results (includes non-coexisting measurements)

When the two 802.11ac Wi-Fi nodes were replaced with LTE-U and the test repeated, the following throughputs were recorded:

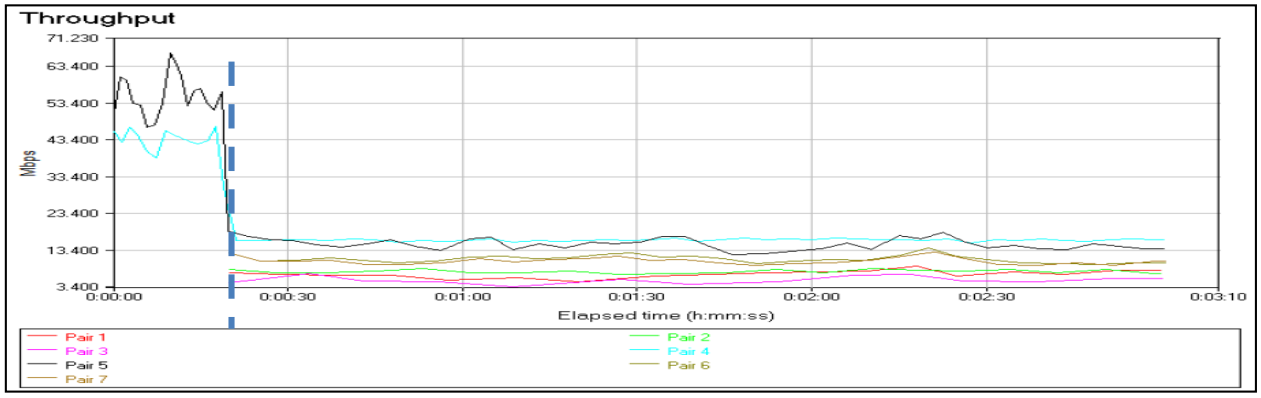

Figure 35 LTE-U and Multi-Vendor 802.11n Multi-Link Coexistence Throughput Results

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
All Pairs	75.119	3.453	67.156	
Pair 1	6.774	4.883	9.138	VENDOR "C" 11N
Pair 2	7.667	6.880	8.507	VENDOR "C" 11N
Pair 3	5.110	3.453	7.041	VENDOR "C" 11N
Pair 4	19.275	15.466	47.163	LTEU- UE1
Pair 5	19.412	12.188	67.156	LTEU- UE2
Pair 6	11.064	9.515	14.162	VENDOR "A" 11N
Pair 7	10.491	9.259	12.921	VENDOR "A" 11N

Table 8 LTE-U and Multi-Vendor 802.11n Multi-Link Coexistence Throughput Results (includes non-coexisting measurements)

The average throughput of the Wi-Fi nodes was 8.2 Mbps.

When the test was repeated with the interferers being received below -72dBm, the following throughputs were recorded:

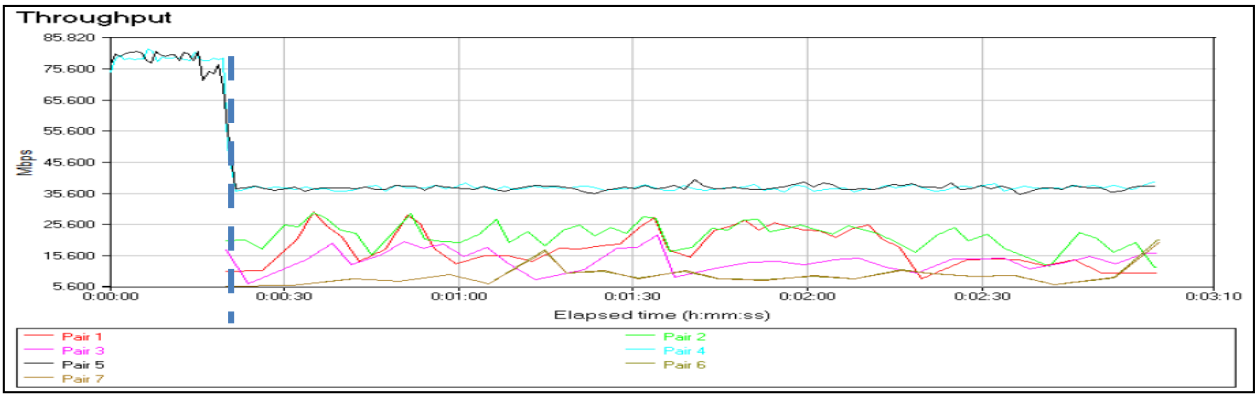

Figure 36 LTE-U and Multi-Vendor 802.11n Multi-Link Coexistence Below -72dBm Throughput Results

Group/ Pair	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)	
All Pairs	145.347	5.641	81.946	
Pair 1	17.382	8.048	29.643	VENDOR "C" 11N
Pair 2	21.620	11.824	29.452	VENDOR "C" 11N
Pair 3	13.429	6.409	22.253	VENDOR "C" 11N
Pair 4	42.097	35.955	81.946	LTEU-UE1
Pair 5	42.145	35.184	81.218	LTEU-UE2
Pair 6	8.411	5.652	20.643	VENDOR "A" 11N
Pair 7	8.395	5.641	19.745	VENDOR "A" 11N

Table 9 LTE-U and Multi-Vendor 802.11n Multi-Link Coexistence Below -72dBm Throughput Results

The average throughput of the Wi-Fi nodes was 13.8 Mbps when the test was run below -72dBm interference at all receivers compared to 8.2 Mbps when the same test was performed at energy levels above -72dBm.

3 Conclusion

LTE-U is an innovative new technology that promises to enhance the user experience for millions of cellular users globally and improve the utilization efficiency of the 5GHz unlicensed spectrum.

LTE-U was designed to coexist with other technologies using the 5GHz spectrum in a technology neutral way. LTE-U equipment achieves this by intelligently selecting the least utilized channel(s) for operation and then continuously adapting the usage of the selected channel(s) based upon the transmissions of other users on the channel.

Extensive Wi-Fi coexistence baseline and LTE-U – Wi-Fi coexistence testing was performed in a variety of different radio conditions both conducted and live-air in order to record and determine the coexistence fairness of LTE-U.

The Wi-Fi equipment used in the tests was representative of real-world deployed equipment, including a mix of 802.11 protocol generations (the vast majority of Wi-Fi devices in use globally are 802.11n) from different major equipment manufacturers. While not exhaustive, the nodes used were highly representative of the real-world installed base of Wi-Fi equipment.

Channel Selection, reselection and coexistence tests were designed to align as closely as possible with the WFA LTE-U Coexistence Test Plan (revision 0.8.0) and modified in order to be executable in the various test environments.

Tests were performed above and below -72dBm, which is the energy detect threshold used by the LTE-U protocol.

The channel selection and reselection tests demonstrate the ability of LTE-U equipment to avoid Wi-Fi networks whenever possible. There are ten (10) 20MHz channels in the U-NII-1 and U-NII-3 band alone. Even in extremely dense deployments such as those found in enterprise or stadium settings, LTE-U channel selection can very effectively avoid the most heavily used channels from its closest neighbors. The ability of LTE-U to perform channel re-selection also allows the LTE-U nodes to adapt to changes in the local RF conditions, for example, due to the introduction of a new transmitter or due to daily traffic pattern changes.

LTE-U channel selection is an extremely effective coexistence procedure.

The co-channel results show that Wi-Fi coexistence behavior is very dependent on equipment vendor and 802.11 protocol generation. Further characterization and baseline performance testing is required in order to more comprehensively record the performance variance of Wi-Fi equipment coexistence.
The co-channel results also confirm that LTE-U coexists fairly with Wi-Fi networks, impacting Wi-Fi end users experience no more than another Wi-Fi network in all the tested scenarios.

The technology neutral LTE-U CSAT procedures provide fair channel coexistence to Wi-Fi and other technologies.

While there are possible deployment scenarios which give rise to poor coexistence from both Wi-Fi to LTE-U and LTE-U to Wi-Fi, these scenarios are likely to be rare and easily avoided by even the simplest network installation planning and LTE-U's channel selection procedures.

The extensive coexistence test results described in this paper demonstrate that LTE-U can benefit millions of users globally while ensuring fair coexistence with Wi-Fi and other technologies.

4 Abbreviations

AP	Access Point
CSAT	Carrier Sense / Adaptive Transmission
DL	Downlink
eNB	3GPP evolved Node-B
GHz	Gigahertz
LTE	3GPP Long Term Evolution
LTE-U	LTE Unlicensed (LTE-U Forum)
Mbps	Megabits per second
QoS	Quality of Service
UL	Uplink
WFA	Wi-Fi Alliance

5 Bibliography & References

a LTE-U Forum www.lteuforum.org